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# Modeling spatiotemporal patterns of building vulnerability and content evacuations before a riverine flood disaster

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A B S T R A C T

In this paper, a spatiotemporal framework is developed for identifying building vulnerabilities and content evacuations during riverine flooding events. This work investigates the spatiotemporal properties required to trigger building contents evacuations in the floodplain during a flood event. The spatial properties for building risks are based on topography, flood inundation, building location, building elevation, and road access to determine five categories of vulnerability, *vulnerable basement*, *flooded basement*, *vulnerable first-floor*, *flooded first-floor*, and *road access*. Using this framework, a model designed to track the spatiotemporal patterns of building evacuations is presented. The model is based upon real-time flood forecast predictions that are linked with building properties to create a model that captures the spatiotemporal ordering of building vulnerabilities and building content evacuations. Applicable to different communities at risk from flooding, the evacuation model is applied to a historical flood for a university campus, demonstrating how the defined elements are used to derive a pattern of vulnerability and evacuation for a campus threatened by severe flooding.



## Introduction

As flooding threatens, vulnerable groups begin the process of moving themselves and their belongings to higher ground. Actions such as sandbag levee construction and the placement of pumps serve as preventative measures against floodwaters, shielding the surrounding infrastructure. All flood response efforts, including protection strategies, require careful planning to effectively position resources as the situation evolves (Faith, Jackson, & Willis, 2011; Jeffers, 2013; Wagner, Chhetri, & Sturm, 2014). These activities demand a well-planned management strategy that is organized within the floodplain so that the impacts of flooding are minimized. In this way, the spatiotemporal dynamics of a forecasted flood are highly important for resource allocation decisions during a serious flood event. In this paper, we present a framework for a spatiotemporal building content evacuation model developed to forecast building vulnerabilities and necessary building content evacuations. The main focus of this research is to investigate the underlying spatiotemporal properties of a model for building evacuations, and the key factors that affect evacuations during a flood event. The model tracks the progression of building evacuations over space and time, revealing the buildings and areas that become vulnerable if the flood event continues. Time is a key element of this model, invoked through aspects including the expected time of flood inundation for both buildings and roads, the time needed to conduct an evacuation, as well as the recommended date-time to evacuate building contents.

Tracking the spatiotemporal pattern of building risks highlights both individual and clusters of building vulnerabilities, giving flood responders important advanced warning. The model output provides building evacuation planning support for decision-makers, for example, staff responsible for facilities management, risk management, public safety, and hydrologists among others. We use buildings on a university campus as an exemplar of the kind of domain for which such a model is useful. While research on trigger buffers for wildfires has identified topography, windspeed, wind direction, and pre-fire fuels as critical elements for modeling evacuations from dangerous wildfires (Cova, Dennison, Kim, & Moritz, 2005; Larsen, Dennison, Cova, & Jones, 2011), in this work, we identify topography, flood inundation, building location, building elevation, and road access as key elements for predicting building vulnerabilities and triggering evacuations of building contents during a flood. The model determines five different classes of vulnerabilities for the evacuation model including *vulnerable*

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*basement*, *flooded basement*, *vulnerable first floor*, *flooded first floor*, and *road access*. Although the geographic space used in testing this model is a university campus, there are many elements in the model that are applicable to other geographic domains including urban evacuations, and the results are generalizable for other communities considering flood mitigation strategies.

Many decision makers use geographic information systems (GIS) to aid in their response efforts (Cova, 1999; Cutter, 2003; Emrich, Cutter, & Paul, 2011; Gunes & Kovel, 2000; National Center for the Study of Counties, 2006). GISs provide a means to analyze and visualize a time-varying flood boundary, representing how this boundary intersects with different parts of a floodplain. This work demonstrates an approach where locations in a domain that are vulnerable to flooding over time are mapped, and form the basis for prioritizing evacuations using information about the spatiotemporal properties of the flood boundary with data about building location, contents and road access to buildings. The contents of buildings at risk from flooding vary widely depending on the purpose for which the building is used, for example, on a campus such contents may include files and office furniture, computers, research laboratory equipment, recreation equipment, and personal belongings in dormitories among others. It should be noted that for this research, our focus is on building content evacuation, and while this does include evacuating occupants of buildings, we do not discuss here route evacuations, i.e., the path that evacuees must take to leave the hazard region. This will be considered in future work with the model.

## Spatiotemporal decision-making and risk analysis approaches during flood events

The use of inundation maps for flood prediction have largely centered on the precision of those maps. Comparisons of inundation maps using varying qualities of terrain data for urban environments have shown that when buildings are captured in the terrain, flood depths and flood extents are improved (Fewtrell, Bates, Horritt, & Hunter, 2008; Kang, 2009; Leitão, 2009). Many inputs that are required for flood model calculations have variables that must be adjusted to fit local conditions. Sensitivity and uncertainty analyses as well as statistical approaches are important methods for providing decision makers with a range of possible outcomes (Crosetto & Tarantola, 2001; Qi & Altinakar, 2011).

Research related to spatial decision support systems (SDSS) for hazard scenarios have investigated spatiotemporal analysis techniques and modeling components. The basic components of an SDSS combine the use of spatial analyses, an information system, and decision support modeling (Densham & Armstrong, 1987; Sugumaran & DeGroote, 2011). An effective SDSS provides its stakeholders with a system that is flexible, solves complex spatial and decision analyses. These computations are then delivered to the stakeholders in a flexible, interactive, and easy to use graphical interface (Sugumaran & DeGroote, 2011). Research on the designing of decision support systems for floods has examined the advantages of using a high performance computing platform with complex models (e.g., statistical and forecast models) (Adorni, 2000) and the visualization of hazard maps for decision makers (Hagemeier-Klose & Wagner, 2009). A real-time system has been developed that utilizes measured or forecasted flood data, exposure information and damage functions to provide decision makers with estimates of damages and losses from flooding (Luino et al., 2009). Methods for ranking flood decisions (priorities) based upon a set of alternatives have also been investigated (Levy, 2005).

Flood modeling depth grids have been used as inputs to modeling risk and damage. Loss estimations for future scenarios, that use current development patterns and current mitigation practices as inputs, have been found to underestimate flood losses by greater than 50% when these datasets are not included in simulations (Hardmeyer & Spencer, 2007). Other uses include estimating damages and losses with and without levees (Remo, Carlson, & Pinter, 2011), accounting for the social impacts (e.g., loss of life, evacuations) due to flooding (Jonkman, Bočkarjova, Kok, & Bernardini, 2008), and determining the overall risk of flooding impacts to a geographic area (Meyer, Scheuer, & Haase, 2009). Internationally, recent work on flood vulnerability analysis has focused on simulations of dam breaches due to earthquakes in China (Li et al., 2013), agricultural impacts in Vietnam (Chau, Holland, Cassells, & Tuohy, 2013), and socio-economic exposures in Chile (Krellenberg, Müller, Schwarz, Höfer, & Welz, 2013).

GIS-based approaches have been widely adopted to provide flood analysis, mapping and decision support. Research on real-time flood response systems examines the ability to create flood extents on the fly (e.g., The Iowa Flood Center) and methods for displaying decision-making information on the web (e.g., http://ut.iihr.uiowa.edu/ifis/en/, http://water.weather.gov/ahps/inundation.php). In addition, due to the development of web technology, web-based GIS has also been discussed and developed to help the decision-making in flood emergencies. The use of NEXRAD, runoff model outputs, hydrologic and hydraulic models has shown to be effective in producing real-time flood extents (Knebl, Yang, Hutchison, & Maidment, 2005; Yang & Tsai, 2000; Yu, Seed, Pu, & Malone, 2005; Van Der Knijff, Younis, & De Roo, 2010; Whiteaker, Robayo, Maidment, & Obenour, 2006). Other work focuses on methods for creating web-based systems for decision-making and alerting. One model utilizes a hydrologic model that is initialized by observations from geosensors and weather forecast data for Europe (Thielen, Bartholmes, Ramos, & de Roo, 2009). In this work, the results of spatiotemporal building vulnerability analyses are displayed using a web-based interface that maps real-time flood conditions and campus vulnerabilities.

Although less attention has been given to building content evacuations, research on evacuating people from hazards is ongoing. For communities and individuals faced with the possibility of being flooded, risk perception is a function of the location and spatial variation of risk (Siebeneck & Cova, 2012). Work on evacuations for hurricanes (involving coastal flooding and hurricane winds) has examined the ability for transportation networks to handle the traffic volumes during an evacuation (Fries, Chowdhury, Ma, & Stephen, 2011; Naghawi & Wolshon, 2010; Wang, Li, Zhou, Nayak, & Chen, 2010). Similar work has examined the ability for transportation networks to support evacuations from fires as well (Cova & Johnson, 2002). In the modeling of the evacuations of people from wildfire hazards, evacuation 'triggers' have been used to determine when people need to leave an area. The triggers are based on the location of a fire, its spread rate, and the distance to a community (Larsen et al., 2011). This method is ideal for planning fire-based scenarios because it does not rely on a single fire ignition location but works for any fires that begin outside of the buffer (Cova et al., 2005). Worst case scenarios have been developed based on the worst case meteorological conditions to drive evacuation route planning during a fire (Dennison, Cova, & Moritz, 2007). Other evacuation trigger examples exist for other hazards. *HURREVAC*, a hurricane evacuation model developed for the Federal Emergency Management Agency, utilizes forecasted hurricane information to produce storm information (e.g., projected windspeeds and storm surge) that provides decision makers with the necessary information to produce evacuation zones (FEMA, 2000). In geographic dynamics research, the modeling of internal and external variation in the attributes of moving objects has been tested in the tracking of storms and near-by vehicles (Pultar, 2010).